Sustainability of Human Exploration in the Artemis Era
A Workshop Report:
Unique Science from the Moon in the Artemis Era

https://ntrs.nasa.gov/citations/20220017053

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“A program of scientific exploration can be constructed this decade whereby science enables human exploration and human exploration enables science.”

From Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology (2023-2032)

Workshop Participants

Over 400 participants at NASA KSC and online (June 2022). Photo captures in-person attendees.

FYI
SCIENCE POLICY NEWS FROM AIP

This Week

Lunar Science Workshop to Scout Out Robot–Astronaut ‘Synergy’

On Tuesday through Thursday, NASA is convening a workshop at Kennedy Space Center that will examine new directions in lunar science enabled by the Artemis crewed exploration campaign. Former NASA Science Mission Directorate head John Grunsfeld will deliver a keynote address on prospects for developing “synergy” between robotics and human exploration. NASA’s integration of science into Artemis drew criticism from the new National Academies planetary science decadal survey, which asserts that plans for crewed missions have insufficiently incorporated science goals and that the agency’s lunar science program is not thinking enough about how astronauts can supplement robotic missions. Grunsfeld, who is a former astronaut, and NASA official Mike Hess will jointly lead workshop sessions on challenges astronauts will encounter in assembling and servicing scientific experiments, and on how astronauts and robots will cooperate in the post-2030 era of NASA’s Commercial Lunar Payload Services (CLPS) program. The CLPS program contracts commercially built and operated robotic landers to convey competitively selected science and technology payloads to the lunar surface at a cadence of about two or three missions per year. The first three CLPS landers are scheduled to launch later this year and just last week NASA selected two science instrument suites that it anticipates sending to the Moon’s mysterious Gruithuisen Domes features “in the 2026 timeframe.”

SPACE.com

News Astronomy Spaceflight The Moon Our Solar System

Hubble-servicing NASA astronaut urges human-robot synergy for future moon missions

By Josh Dinner published August 11, 2022

'All robotic exploration is really a human-robotic partnership. How do we amplify the science in this human-robotic partnership?'

NASA's Space Launch System (SLS) rocket with the Orion spacecraft aboard is seen at sunrise atop a mobile launcher at Launch Complex 39B, Monday, April 4, 2022. (Image credit: NASA/Joel Kowsky)

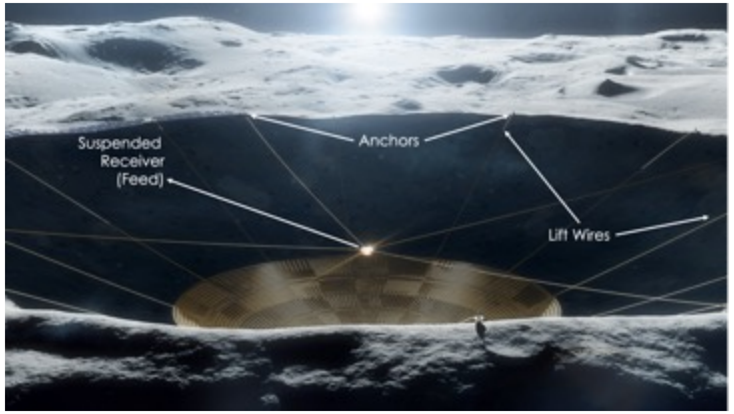
NASA astronaut John Grunsfeld cited some less than stellar findings during a keynote speech in June at NASA's Kennedy Space Center (KSC) Visitor Complex, says waiting to integrate science objectives directly into foundational mission hardware prohibits our exploration potential.

NASA's Engineering & Safety Center (NESC) sponsored a workshop entitled "Unique Science from the Moon in the Artemis Era." The three-day long conference focused on the various engineering obstacles associated with utilization of the lunar environment for possible astronomical science experiments as part of NASA's Artemis missions, like the Lunar Crater Radio Telescope (LCRT), and the challenges faced regarding astronauts' assembly and maintenance of scientific experiments and spaceflight infrastructure.

Workshop Key Takeaways

- Future science decadal surveys should **consider use of human exploration capabilities as viable options for meeting decadal-level science objectives.** The Hubble Space Telescope (HST) is a shining example!
- While the lunar surface environment is challenging, with dust contamination and maintaining a far-side radio quiet zone being the major concerns, **no showstoppers to using the Moon as a platform for science observatories were identified.**
- To enable in-space servicing, assembly, and manufacturing, **design of future observatories or instruments deployed on the lunar surface should follow the HST model, where standards are followed to make them astronaut friendly** (e.g., standard bolt sizes, easily accessible avionics, avoidance of sharp edges).
- To **ensure safety of the crew on prolonged missions, early environmental testing should be conducted** for life support system tolerances and hardware exposure impacts during initial Artemis missions.
- To **ensure Artemis sustainability**, the Science Mission Directorate (SMD) and the Exploration Systems Development Mission Directorate (ESDMD) should collaboratively identify mission requirements beyond Artemis IV to **accomplish decadal-level science via human exploration missions.**

Astronauts Servicing HST

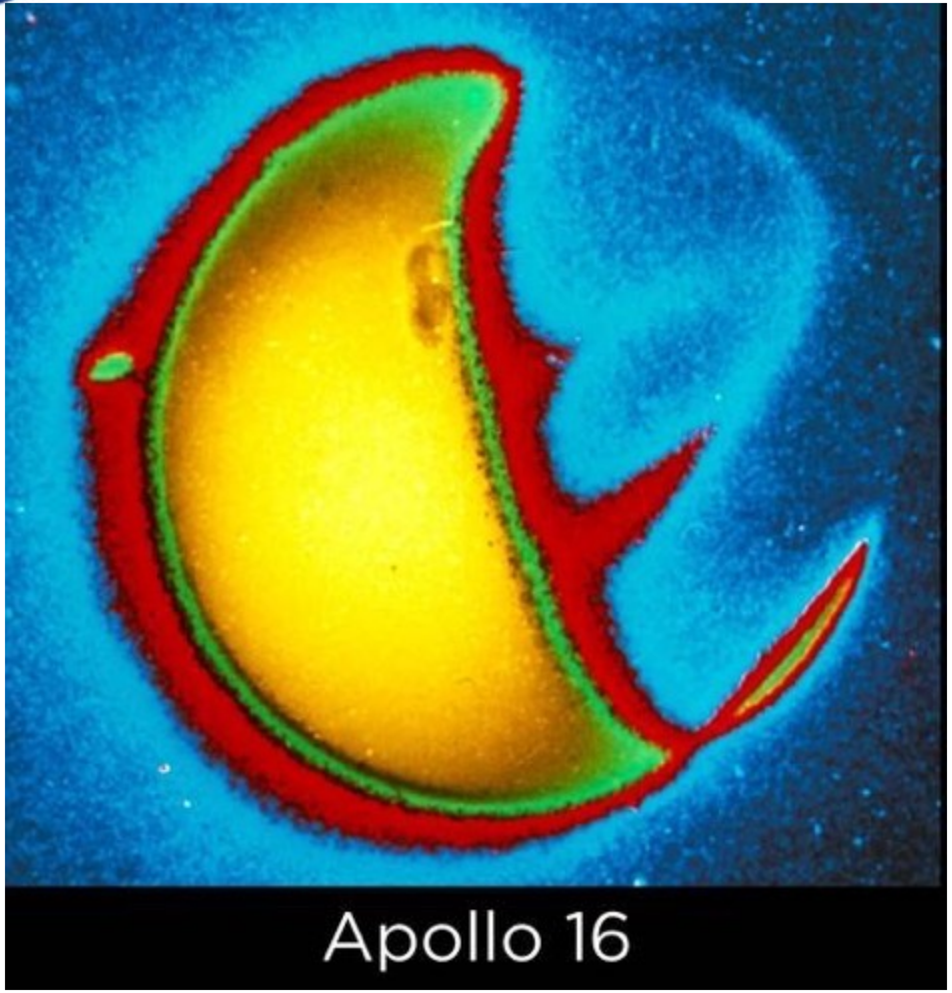


Lunar Crater Radio Telescope Concept

The Moon:
A Platform for Unique Scientific Discoveries

Realizing use of the Moon as a platform for science will require high-priority science and mission endorsements from future decadal surveys.

First View of the Earth from the Moon



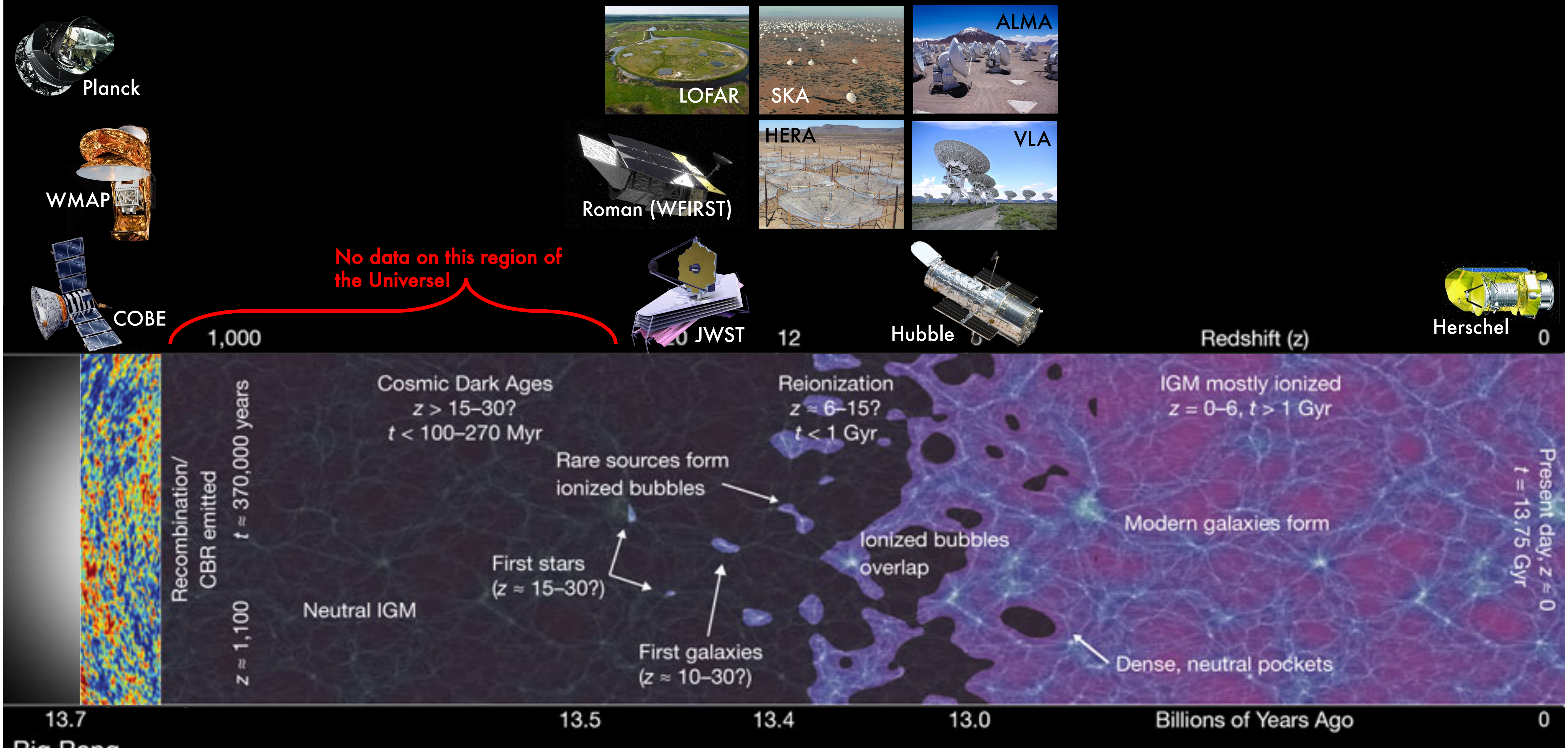
Far ultraviolet image of the Earth taken from the lunar surface during Apollo 16 by John Young and Charles Duke

First lunar telescope (PI: George Carruthers)

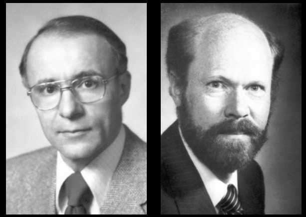
President Barack Obama presented Dr. Carruthers with the National Medal of Technology and Innovation in 2013.

George Carruthers, center, in 1971. A telescopic device he designed was used on the Apollo 16 mission to produce images of the geocorona, Earth's outermost atmosphere, as well as stars, nebulae and galaxies. NASA/Kennedy Space Center

Evolution of the Universe



Nobel Prizes in Cosmology



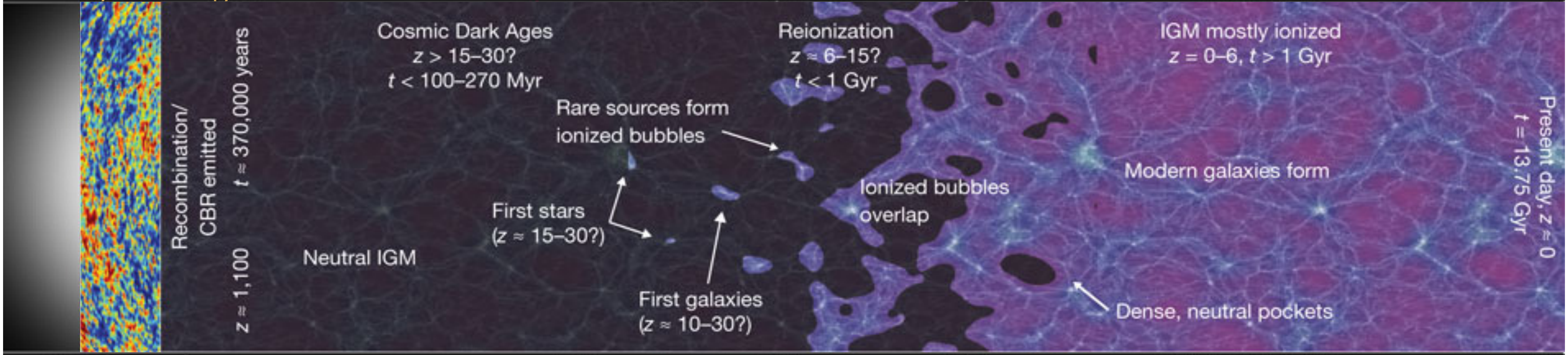
A. Penzias, R. Wilson (1978)
"Discovery of CMBR"

J. Mather, G. Smoot, (2006)
"Discovery of anisotropy in CMBR"

S. Perlmutter, B. Schmidt, A. Riess (2011)
"Discovery of the accelerating expansion of the Universe through observations of distant supernovae."

James Peebles (2019)
"Theoretical discoveries in physical cosmology"

No data on this region of the Universe!

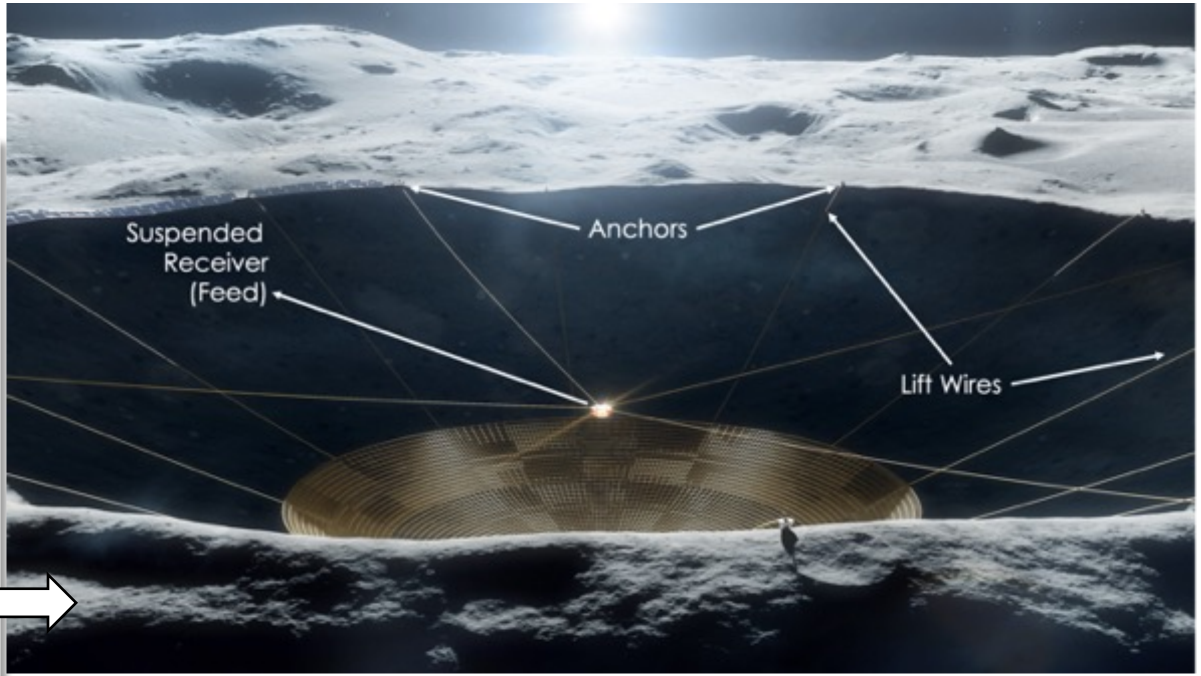


Next Generation Radio Observatory from the Moon

Arecibo Observatory (1963-2000)

The National Science Foundation announced last week that it will not be rebuilding the observatory.

Lunar Crater Radio Telescope Concept (2030s?)



- 5- to 50-MHz radio frequency poorly explored.
- Radio telescope on the far side of the Moon allows observation in this band (Moon physically shields from Earth's noise).
- When built, has the potential to be the largest radio telescope in the solar system!

Engineering Challenges and Risk Mitigation Strategies

While the lunar surface environment is challenging, with dust contamination and maintaining a far-side radio quiet zone being the major concerns, no showstoppers to using the Moon as a platform for science observatories were identified.

Lunar Challenges Examined

- Dust and charging
- Communication and navigation
- Preserving the radio-quiet environment of the Moon
- Extreme thermal environment
- Power generation and storage
- Lighting and worksite design

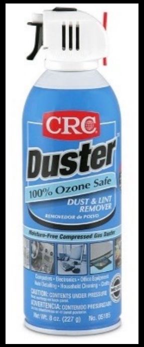
Dust Mitigation Solutions

Architectural Solutions

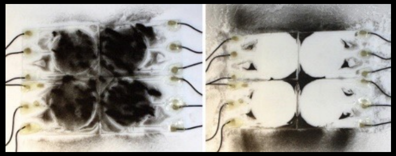
Operational Solutions

Passive Technologies

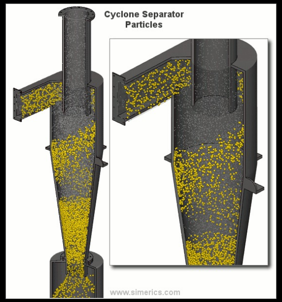
Active Technologies

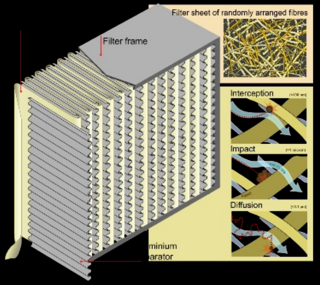


- Active technology solutions:
- Electrostatics
- Compressed air
- Vacuums
- Electrodynamic dust shield



- Passive technology solutions:
- HEPA filters
- Cyclone separators
- Softwalls
- Low-energy surface coatings
- Coveralls/aprons
- Dust tarps
- Brushes
- Tape
- Wipes



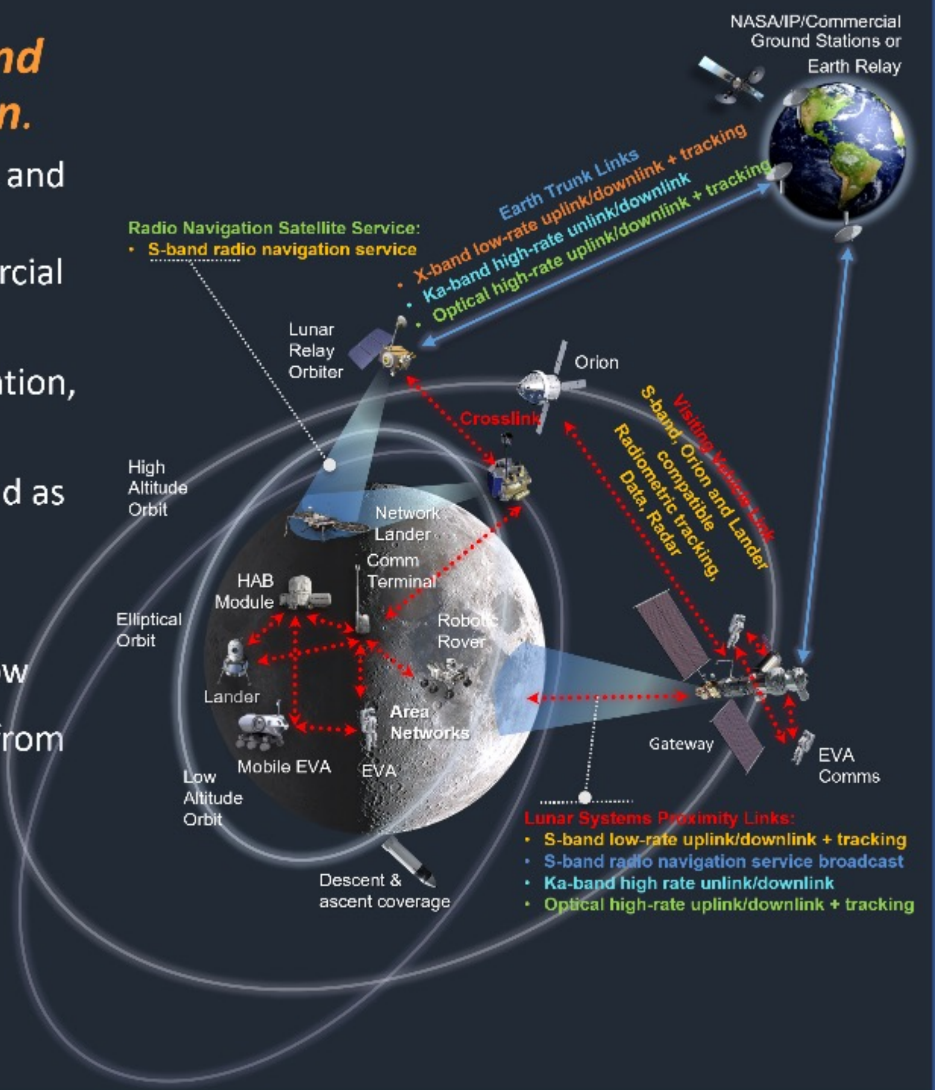


Architectural & Operational solutions:

- Suitports
- Severable airlocks
- Mud-rooms
- Porches
- Landing Site Selection
- Prepared Landing Pad
- Optimized EVA and traverse planning

Communication and Navigation

- ***LunaNet is the lunar Internet – a set of cooperating networks providing interoperable communications and navigation services for users on and around the Moon.***
  - Based on a framework of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability
  - Allows many mission users to benefit from services of diverse commercial and government service providers
- **Service-Oriented:** Services include data transmission; Position, Navigation, and Timing (PNT); and situational awareness information
- **Scalable**: Introduce minimal capability for earliest missions and expand as needed for new users and service providers
- **Open**: Based on open international standards like the Internet
- **Resilient**: Resilience to failures and outages increases as networks grow
- **Secure**: Protect sensitive data while preventing or rapidly recovering from cyber threats
- **Extensible**: Apply the LunaNet concept to any planetary body



Maintaining the Radio-quiet Environment on the Far Side

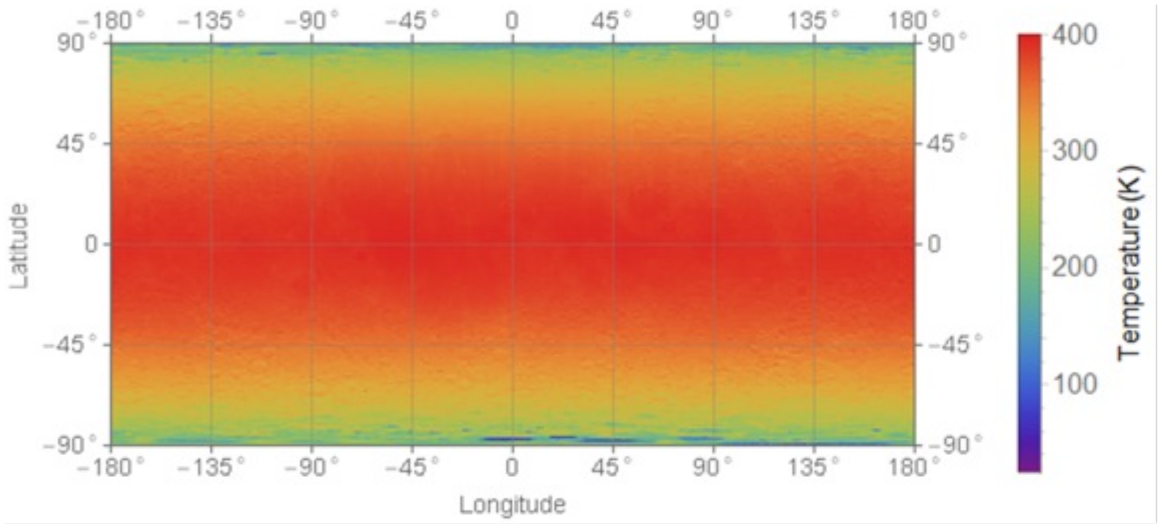
- Radio-frequency interference (RFI) can corrupt science measurements.
- Difficult to correct or compensate.
- Radio astronomy is particularly sensitive to RFI.

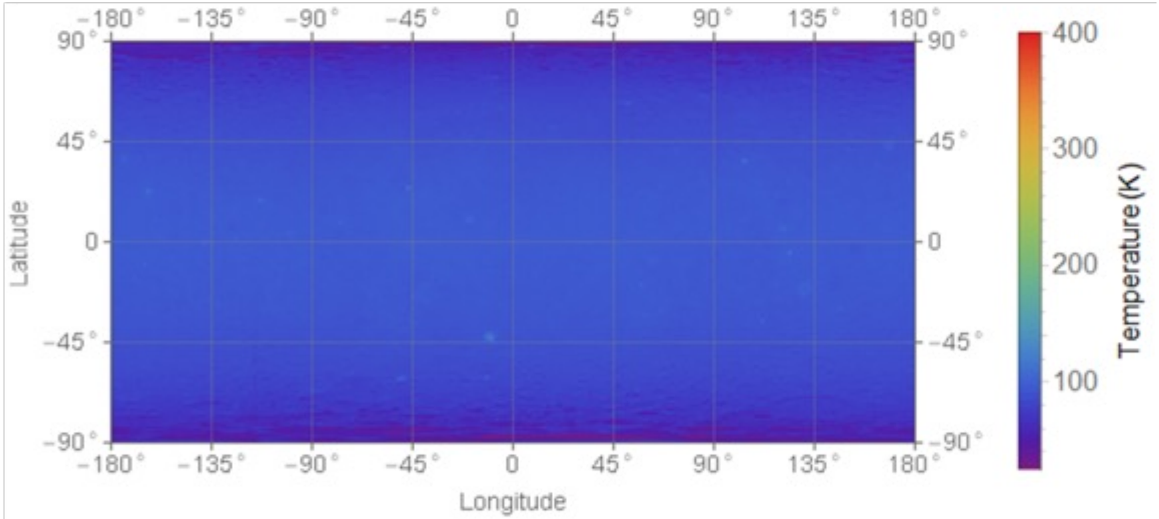
- Frequencies of scientific interest are lower than typically used for spacecraft communication.
- Major concern in maintaining is broadband emitters (i.e., switching circuits, motors, and digital noise from computers).

- Maintaining the shielded zone of the Moon (SZM) requires standards and international cooperation.

Extreme Thermal Environment

Maximum Lunar Temperatures



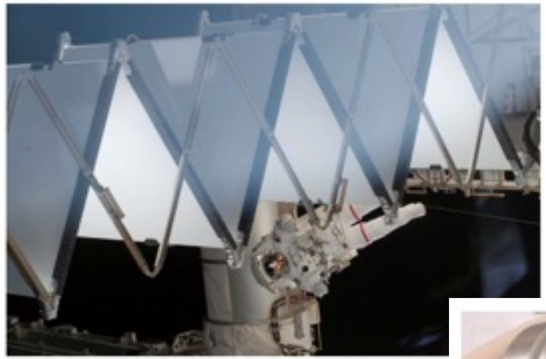


Minimum Lunar Temperatures

Thermal technologies for surviving extreme lunar environment

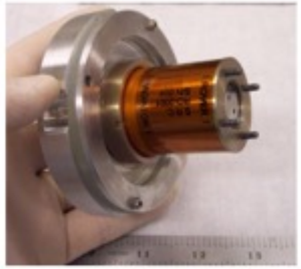
- Advanced radiators
- Thermal switching devices
- Active heating
- Thermal storage (passive heating)
- Insulation

Various types of multilayer insulation



ISS deployable radiators

Radioisotope heater unit

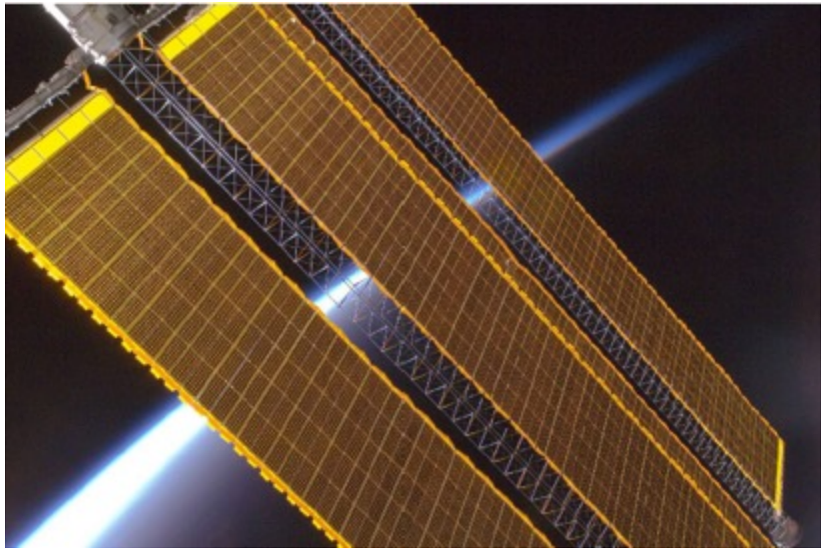


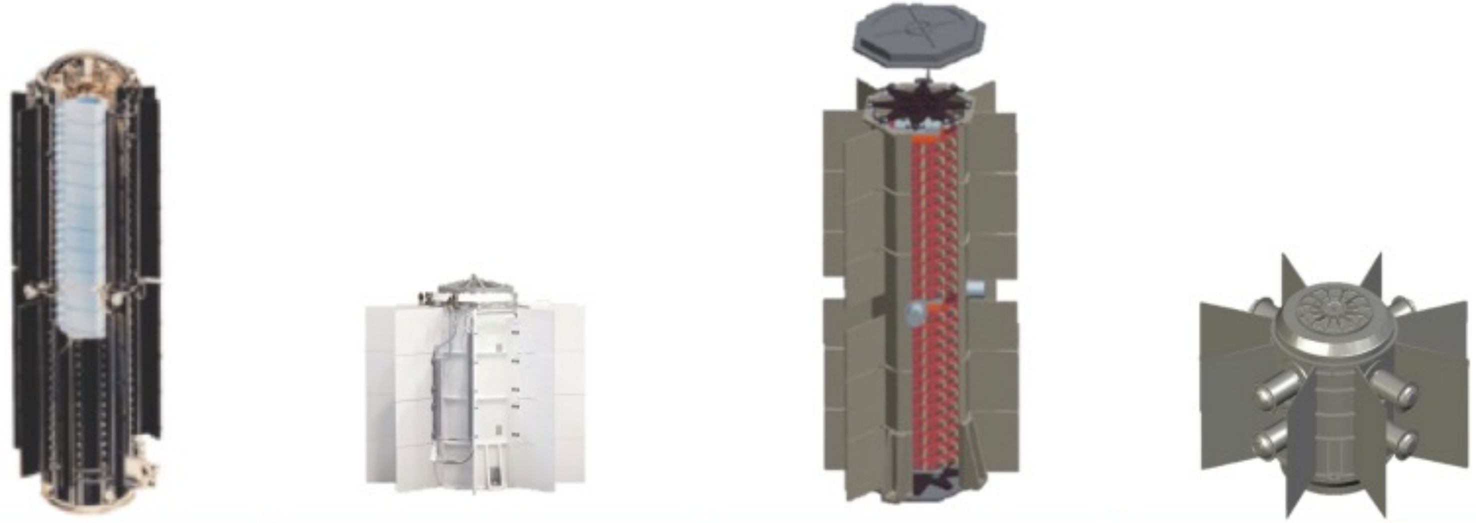
Paraffin heat switch

Heaters applied to a Mars Science Laboratory propellant tank

Power Generation and Storage Technologies

- Solar cells
- Solar panels
- Solar arrays
- Radioisotope power systems
- Fission power systems
- Regenerative fuel cells
- Rechargeable batteries

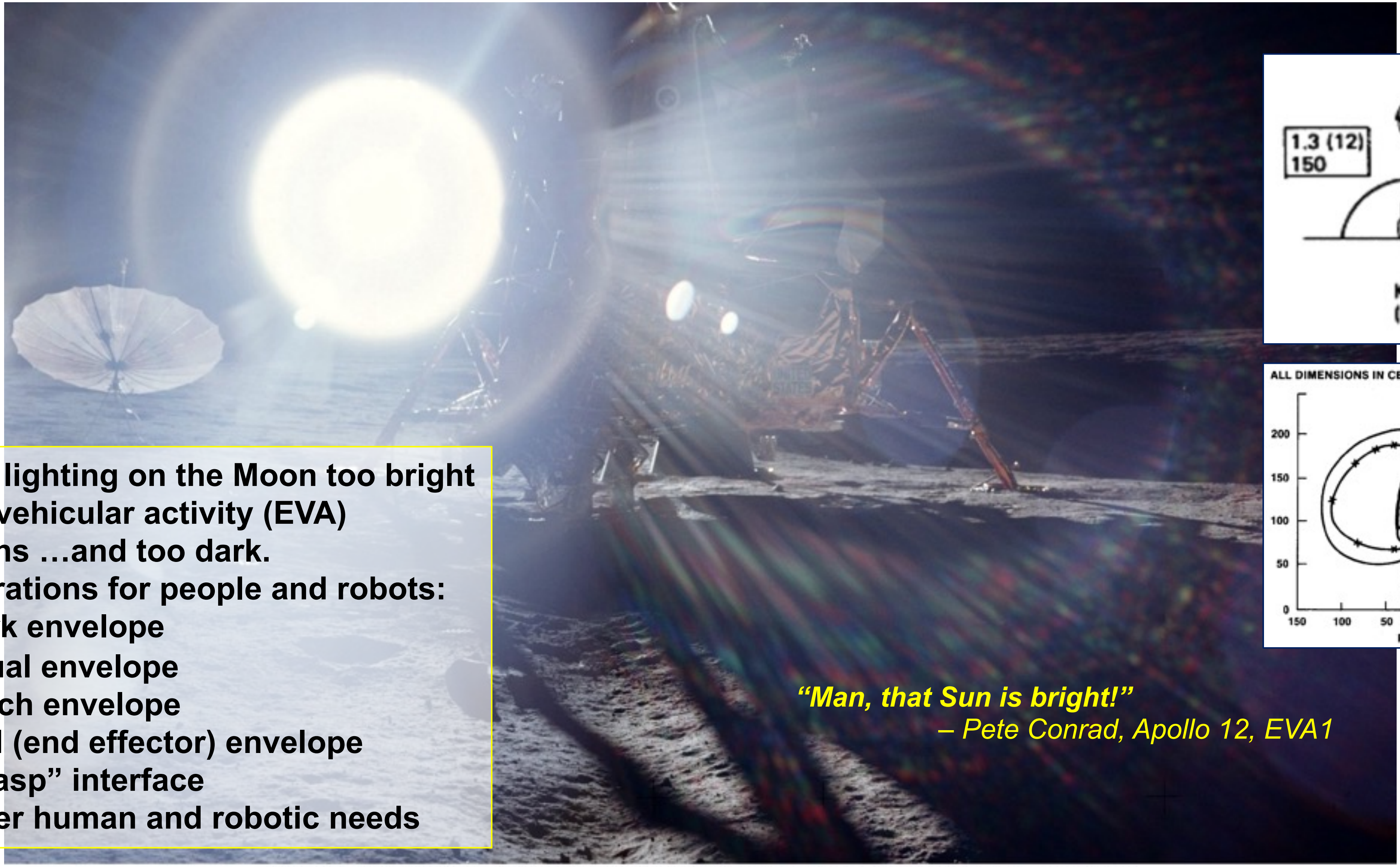




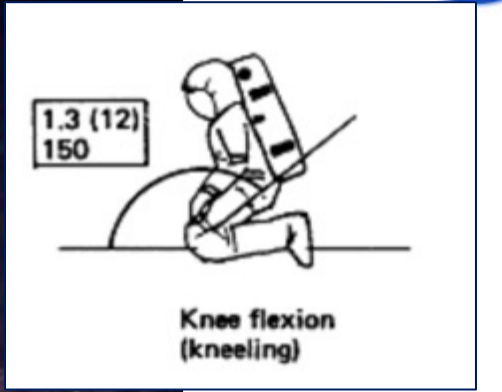
GPHS-RTG | MMRTG | Next Gen RTG | DRPS

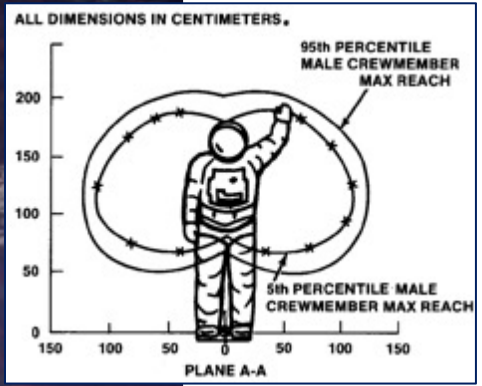
1-10kWe Fission Power System Concept

Lighting and Worksite Design



- ❖ **Ambient lighting on the Moon too bright for extravehicular activity (EVA) operations …and too dark.**
- ❖ **Considerations for people and robots:**
  - ❖ **Work envelope**
  - ❖ **Visual envelope**
  - ❖ **Reach envelope**
  - ❖ **Tool (end effector) envelope**
  - ❖ **“Grasp” interface**
  - ❖ **Other human and robotic needs**



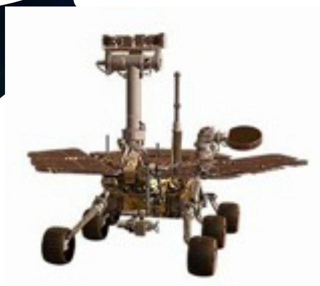


Apollo 12, Ocean of Storms, EVA 1, 19 November 1969, frames A12-46-6738 to 6740 : Apollo 12 landing site

Synergy Between Human and Robotic Exploration

To enable servicing, design of future observatories or instruments deployed on the lunar surface should follow the HST and International Space Station (ISS) models, where standards are followed to make them astronaut friendly for servicing.

Human/Robotic Lunar Science Exploration in the Artemis Era

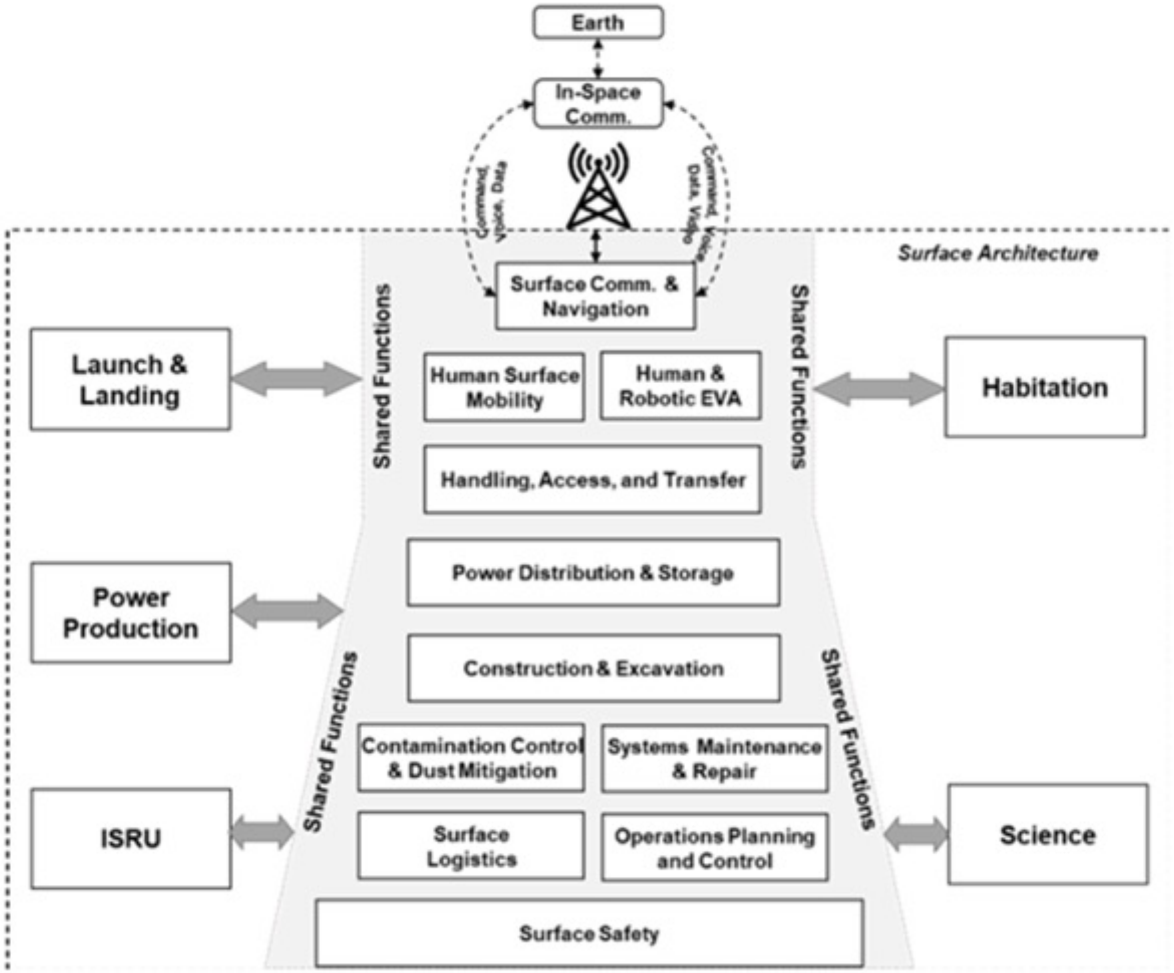


- **The combination of robotic and astronaut capabilities, especially when working together, offers the opportunity to expand the scientific utilization of the Moon** to include heliophysics, Earth observation, and astrophysics.
  - Expect increased human and robotic surface cooperation.
- **The 2023-2032 Planetary Decadal Survey notes that a robust science program provides the motivating rationale for sustained human exploration.**
  - Workshop concurs that NASA’s organizational structure should incorporate science into human exploration (with proactive planning and objectives, not reactive).
- **How do I plan for a lunar worksite?**
  - **Design for standard EVA and robotic interfaces** – NASA-STD-3001 articulates many of the standards for suited and unsuited crew members for reach, visibility, and other capabilities.
  - **Design for servicing and maintenance -** to enable servicing on the Moon, follow the HST and ISS models to make them astronaut friendly for servicing (e.g., standard bolt sizes, easily accessible electronics cards, avoidance of sharp edges).
  - **Human assembly of scientific instruments** or observatories on the lunar surface **should focus on items that cannot be affordably and technically implemented by robots.**

Leveraging Artemis Era Infrastructure

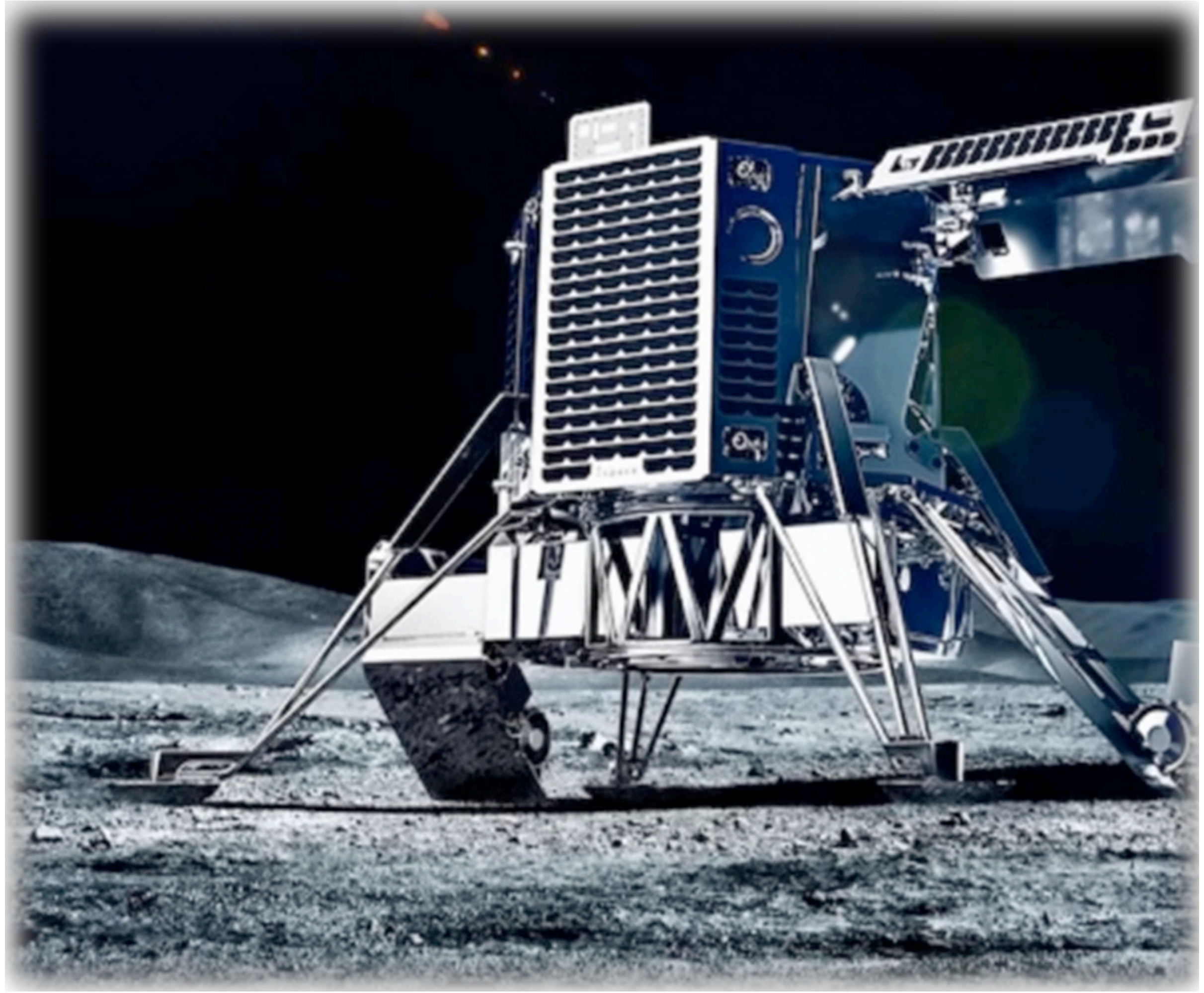
- **Leverage Artemis era infrastructure -** infrastructure essential for EVAs in the Artemis era should include a home base that provides crew habitat, consumables recharge station, high-bandwidth communication relays, and rapid Earth return for safety.
    - Science mission development, operations, maintenance, and servicing should take advantage of all NASA assets. Don't stovepipe!
    - To avoid costly and potentially hazardous designs, systems engineering for both science payloads and exploration capabilities must bridge the HQ mission directorate stovepipes.
- **Include international and interagency partnerships to achieve science objectives.**
    - European Space Agency (ESA) interest in lunar far-side low-frequency radio telescope array.
    - Department of Energy Office of High Energy Physics desire to address questions involving the early Universe—dark matter, dark energy, and cosmic inflation.

…opportunities for breakthrough-level decadal science!



Sustainable Lunar Exploration

- **Proposed Artemis mission requirements for sustained scientific exploration**
  - The merging of science and human exploration presents a unique challenge compared with the typical manner in which robotic science missions are formulated.
  - For Artemis IV and beyond, the science requirements need to be captured with an up-front Science Definition Team (SDT) process for both large strategic observatories and more modest "Explorer class" competed opportunities.
- **Delivery of scientific payloads to the lunar surface in the late 2020s and beyond may require larger down-mass and volumes than the current CLPS capabilities.**
  - Planning future requirements for CLPS 2.0 based on possible scientific investigations should begin now to prepare for future decadal surveys (i.e., Astro2030 and Planetary 2032).



NASA's Moon to Mars Objectives

Draft Objectives (May 2022)

Astrophysics Science (AS) Goal: Preserve the far side of the Moon as a "radio-free zone" for future radio astronomy experiments.

AS-1: Monitor the radiofrequency environment on the lunar far side to enable future far side radioastronomy activities.

Revised Objectives Unveiled at IAC (September 2022)

Physics and Physical Science (PPS) Goal: Address high priority physics and physical science questions that are best accomplished by using unique attributes of the lunar environment.

PPS-1[L]:	Conduct astrophysics and fundamental physics investigations of space and time from the radio quiet environment of the lunar far side.
PPS-2[LM]:	Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.

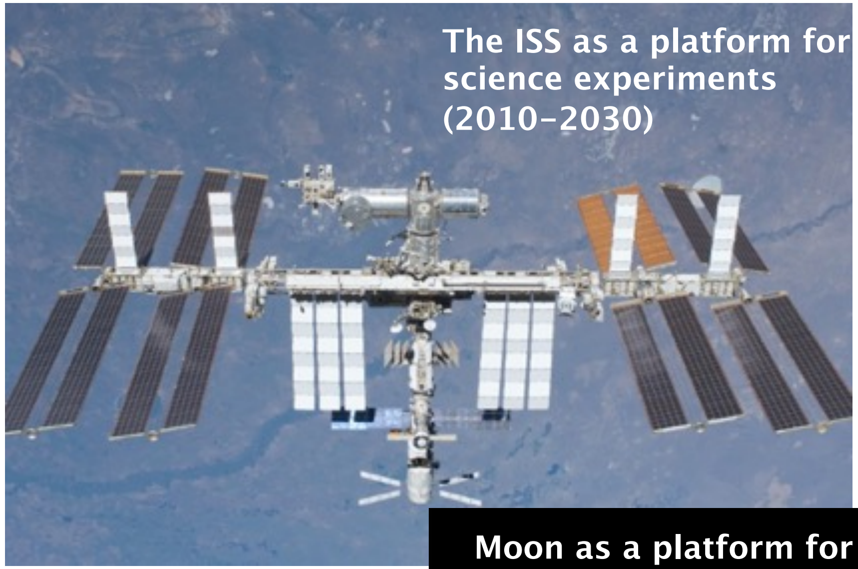
Final Thoughts:
Sustainability of the Artemis Era

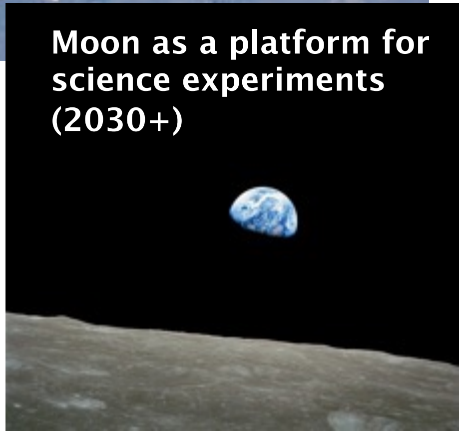
HST and ISS are shining examples of sustainability when science and human exploration programs work together.

- Beyond Artemis IV, the SMD and the ESDMD should continue to be empowered to collaboratively define mission requirements to **accomplish decadal-level science via human exploration missions.**

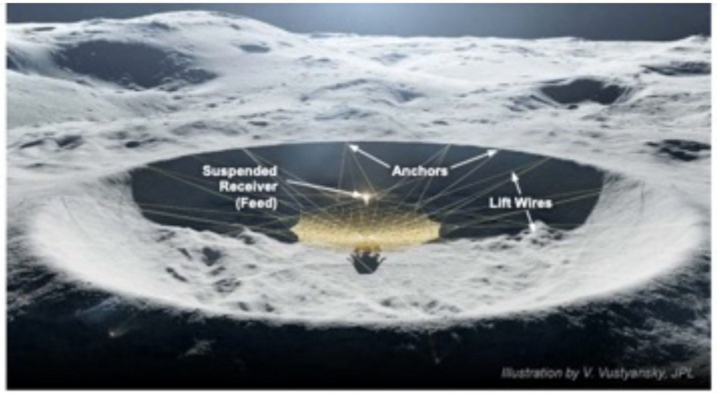
- **To enable servicing, design of future observatories or instruments deployed on the lunar surface should follow the HST and ISS models, where standards are followed** to make them astronaut friendly for servicing.

HST 1990–present





SCIENCE
Dr. Azita Valinia,
NESC Chief Scientist



HOW DO WE SUSTAIN HUMAN EXPLORATION IN THE ARTEMIS ERA?

Planning is underway at NASA for returning humans to the Moon, followed by human missions to Mars. Astronauts will again venture outside the protective shield of the Earth's magnetosphere, this time for durations of months to several years, where they will be vulnerable to long-term exposure from radiation and microgravity or low gravity environments. Keeping the astronauts safe and healthy during these long-term expeditions is an enormous challenge and so is the enormous price tag that comes with accomplishing such a grand feat. So what will keep such endeavors sustainable after the novelty of "been there" and "done that" wears off? The answer is simple: Science! Making groundbreaking discoveries spanning pure and applied sciences as a key part of Artemis goals provides a long-term sustaining rationale, beyond just exploration for its own sake. The success of the Hubble Space Telescope (HST) servicing missions to upgrade and repair the telescope to advance astrophysics is a shining example of what can be accomplished when NASA human exploration and science programs partner towards a common goal.

The Moon – A Platform for Science

Scientific exploration, whether of the Moon itself, or the use of the Moon as a platform for scientific studies, will play a great role in fueling sustainable human exploration. For example, since the beginning of the space age, the Moon has been proposed as a platform for astronomical observatories. With the NASA Artemis plan to return humans to the lunar surface in the mid-2020s, there is renewed interest in using the Moon as a unique location for scientific studies ranging from observing our solar system to studying the early universe before the first stars were born. Great opportunities lie ahead to advance ground-breaking science using the synergy between human and robotic scientific exploration. For this reason, a workshop, *Unique Science from the Moon in the Artemis Era,*[1] bringing together stakeholders from science, engineering, technology, and human exploration communities was sponsored by the NESC in June 2022 to accomplish the following:

- Explore leveraging Artemis-era infrastructure to conduct unique science experiments and observations from the lunar surface and maximize return on investments,
- Advance synergistic approaches between human and scientific robotic exploration, and
- Identify/address key engineering challenges and risks.

Over 400 attendees participated in the hybrid workshop that was held at KSC and online. The workshop began by identifying unique and compelling astrophysics science studies that can only be accomplished from the surface of the Moon. Among the possibilities, the workshop focused on studies that NASA has already funded to robotically place a low-frequency radio telescope on the far side of the Moon[3] to study the Dark Ages of the Universe (the epoch before the first stars were born) and radio emissions from the Sun and exoplanets orbiting nearby stars. One of these studies focused on placing a low-frequency radio telescope (Lunar Crater Radio Telescope[2]) inside a lunar crater. If built as proposed, it will be one of the largest radio telescopes in the solar system and would enable tremendous scientific discoveries in cosmology. While it is feasible that such a telescope could be assembled robotically, leveraging the Artemis infrastructure has the potential to be more efficient and cost effective.

Achieving Synergy Between Human and Robotic Exploration

A key element of the NESC workshop was to identify how the human exploration program can be leveraged to achieve ground-breaking science. There have been past successful examples of this, with the most spectacular being the Space Shuttle launch of the HST and subsequent servicing missions. More recently, this has been accomplished via science experiments attached to the ISS. For a future lunar base camp with science facilities, there are analogies with the Amundsen-Scott South Pole Station in Antarctica, which provides a hub for scientific activities, including telescopes to study the cosmic microwave background and neutrino experiments.

Exploiting the infrastructure provided by the human exploration program will have major benefits both in cost savings to the science program and its sustainability (e.g., via potential upgrades and repairs of facilities). As demonstrated by HST and the ISS, there is the potential for major groundbreaking science to be achieved when the human and science programs work together. Currently, science requirements are retrofitted to the capabilities of the early Artemis missions. This is understandable given that early missions are to demonstrate basic capabilities, but this limits the science return. Just as the later Apollo missions made science a driving goal with increased capabilities,

Top: Illustration depicting the concept of the Lunar Crater Radio Telescope on the far side of the Moon. Middle: Astronaut John Grunsfeld servicing HST. Bottom Left: Grunsfeld giving the keynote speech on synergy between science and human exploration. Bottom Right: NESC Workshop, "Unique Science from the Moon in the Artemis Era", held July 2022 drew over 400 participants at KSC and online.

the workshop concluded that we must be vigilant to ensure that science requirements are not afterthoughts for Artemis missions in the 2030s and 2040s. It is critical that architectural elements to enable ground breaking science be included in the Artemis requirements at an early stage of the Artemis Program.

A focus of the workshop was the synergy between human and robotic scientific exploration. The presence of humans on the lunar surface is an opportunity to deploy, repair, and upgrade any scientific instruments and observatories there. It is essential to optimize the role of robotics versus humans and to only use the latter where appropriate. A key feature is to ensure that telescopes that have been robotically landed and deployed, or those that have been manufactured in situ, are designed to be serviced. In a keynote speech, former astronaut John Grunsfeld discussed the lessons learned from HST and the ISS and made the compelling point that having standards (e.g., using the same bolt sizes and accessible connectors, and providing easy access) is crucial. This provides the ability to recover from unexpected events and failures, as well as upgrade existing facilities with new technology, ensuring sustainability.

Meeting the Engineering Challenges & Risks

Engineering challenges and risks associated with synergistic human and robotic exploration was another discussion focus of the workshop. While the lunar surface environment is challenging with dust contamination, large thermal swings, and extreme shadows at the lunar poles, and power generation and storage technologies will need to be developed, no show-stoppers to using the Moon as a platform for science observatories were identified, but careful planning is needed. For example, adequate low-frequency radio frequency interference testing, screening, and shielding must be considered and standardized for all spacecraft and payloads that will be visible from the lunar radio quiet zone.

In summary, to ensure sustainability of the human exploration program and provide added return on investment, the workshop concluded that integration of science requirements into the Artemis Program at an early stage is a must. Otherwise, human exploration that does not include science as one of the primary objectives is a missed opportunity and is likely to result in the exploration program not being sustainable.

1. https://www.nasa.gov/nesc/workshops/Unique-Science-from-the-Moon-in-the-Artemis-Era
2. https://www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/lunar_crater_radio_telescope/
3. Observations of the radio band below 30 MHz cannot be made from the ground due to absorption from the Earth's ionosphere. These observations can only be made from the far side of the Moon since the Moon acts as a physical shield that isolates the telescope from radio interference from sources on and around the Earth's orbit.

https://www.nasa.gov/sites/default/files/atoms/files/techup_2022_web_2page.pdf